GaN-Based Lasers on SiC: Influence of Mirror Reflectivity on L-I Characteristics

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Threshold current density and differential slope efficiency as function of end-mirror reflectance have been measured to estimate the internal losses of GaN-based laser diodes. An Al-coated fiber tip is used as an external micro-mirror to vary the reflectance of the end facets allowing for a continuous adjustment of mirror losses of a particular laser. The effective reflectance of the external resonator is modeled as function of facet reflectivities, emission wavelength, micro-mirror distance and laser mode shape. In contrast to other methods, this eliminates all ambiguities usually arising from the comparison of devices of varying length or mirror coatings. In GaN-lasers with high threshold current transparency loss for the gain medium is not negligible and, therefore, $i_{th}$ dependence on mirror reflectivity alone is not sufficient to determine internal losses. Our measurements of one-facet slope efficiency yields internal losses $\langle \alpha_{int} \rangle$ between 27 cm$^{-1}$ and 46 cm$^{-1}$ whereas for derivation from current threshold a combination of transparency and internal losses in the range of 58 cm$^{-1}$ to 67 cm$^{-1}$ has been obtained.

1. Introduction

Whereas blue and green light emitting diodes (LEDs) have already been successfully commercialized, ultraviolet laser diodes (LDs) are still challenging for epitaxial growth and process technology arising from the specific material properties [1]. The low refractive index of GaN at 400 nm leads to a significantly reduced mirror reflectance of 0.18 according Fresnel equations. The mirror reflectance is further decreased by any interface roughness, as it typically appears for all dry chemical etched laser facets [3]. The weak dependence of refractive index on Al-content together with epitaxial limits on Al-content and AlGaN thickness yield a relatively poor optical confinement. Furthermore, due to the high number of dislocations acting as scattering centers the waveguide is susceptible to absorption losses. Since mirror losses have been overcome either by HR coating with dielectric $\lambda/4$ mirrors or usage of SiC and GaN substrates which allow cleaving, internal losses have moved into focus for further device optimization.

Usually, the internal losses are estimated from laser threshold of different cavity lengths and mirror coatings. Using different devices might cause ambiguities due to epitaxial inhomogeneity and various processing. Laser diodes relying on cleaved or etched GaN/air facets are quite sensitive to external optical feedback. An external micro-mirror can,
therefore, be used to increase the effective mirror reflectance significantly. Moreover, changes in the distance between the butt coupled micro-mirror and the facet influence the feedback into the laser diode, so an adjustable facet reflectance can be realized [2]. In this paper, we present the estimation of internal losses and transparency losses by continuous variation of mirror reflectivity on a single diode.

2. Experimental Setup

The devices under investigation are separate confinement double heterostructure (SCH) lasers grown by MOVPE on SiC substrates. Oxide stripe lasers have been fabricated from those structures with a 600 μm x 6 μm geometry. The facets are formed by cleaving the thinned substrate. Within this study laser diodes with one highly reflecting (HR) and one uncoated facet are used. The HR-coating consists of a stack of λ/4 dielectric layers and has a nominal reflectance of 0.95 to 0.98. Further details concerning structure and chip technology are reported elsewhere [4]. Fig. 1a shows the experimental setup. A cleaved fiber facet with 100 μm diameter and a 200 nm thick Al-coating is used as an external micro-mirror. Within the examined wavelength range between 400 nm and 410 nm the reflectance of the mirror is estimated of about 0.91. To align the micro-mirror in front of the uncoated laser facet, a piezo controlled xyz-stage with a resolution of approximately 10 nm is used. The optical output power of the laser diode is collected from the HR-coated facet by a microscope objective and imaged on a photodiode. To allow for correction of additional tilt errors the sample is mounted on a 4-axis waveguide manipulator. For measuring the L-I characteristics the device is biased with a current of 1 mA and driven by 50 ns long pulses at a duty cycle of 0.05%.
Fig. 2. (a) Calculated effective reflectance $R_{2,\text{eff}}$ as function of micro-mirror distance from uncoated laser facet ($R_1 = 0.91$, $R_2 = 0.18$). The observed exponential decay is due to divergence of the laser beam which leads for increasing distance $d$ to reduced back-reflection into the laser mode. Additional curves represent lowered values of the uncoated facet reflectance $R_2$, typically induced by surface roughness due to dry-etching. (b) L-I characteristics taken from the HR-coated facet for different positions of the micro-mirror corresponding to various effective reflectances $R_{2,\text{eff}}$. For increasing values of $R_{2,\text{eff}}$ significant threshold current reduction and improved slope efficiency is observed.

3. Results and Discussion

Fig. 1b shows the optical output power measured from the HR-coated facet at constant current as a function of mirror distance $d$ to the uncoated facet. The output power reveals characteristic Fabry-Perot resonances resulting from coupling a second external resonator which is formed by the uncoated GaN facet, the air gap and the micro-mirror. Since the laser beam diverges, towards larger distances $d$ the overlap of back-reflected optical field and the laser diode’s mode profile decreases. This weakens the overall feedback into the laser shown by an exponential decay which envelopes the output power oscillations. For estimation of internal losses the system is treated as a solitary laser diode substituting the external resonator by an output facet with variable effective reflectance $R_{2,\text{eff}}(d)$. Modeling of $R_{2,\text{eff}}(d)$ is a crucial point for the following considerations and takes into account the reflectance of the HR-coated facet $R_1$, the uncoated GaN-facet $R_2$ and
micro-mirror $R_m$, emission wavelength $\lambda$, micro-mirror distance $d$ and laser mode shape. The mode shape was calculated by a waveguide simulation program and confirmed by far field measurements. Losses because of divergence are taken into account by propagating the beam twice the air resonator length and calculating the overlap of beam profile with the laser mode. In Fig. 2a the calculated effective reflectance $R_{2,\text{eff}}(d)$ is plotted for $R_m = 0.9$ and $R_2 = 0.18$. The qualitative shape of the of the $R_2$ versa $d$ dependence is similar to that of the measured output power, featuring same strong oscillation and characteristic exponential decay. Additional envelopes sketch the influence of reduced $R_2$ as it is typically obtained for increased surface roughness due to dry-etching. Atomic force microscopy (AFM) measurements on the laser facets revealed a root mean square surface roughness of the cleaved facets of about 1 nm indicating that the roughness is not a significant factor [5]. Therefore, in the following considerations a reflectance $R_1 = 0.18$ for the uncoated GaN-facet is used. Fig. 2b depicts I-L-characteristics taken from the HR-coated facet for different positions of the micro-mirror corresponding to various effective reflectances $R_{2,\text{eff}}$. The expected dependence of slope efficiency $\eta_s$ and $i_{th}$ on mirror reflectivity is experimentally verified. For increasing values of $R_{2,\text{eff}}$ significant threshold current reduction and improved slope efficiency are observed. When the micro-mirror is in close proximity of the facet corresponding to the highest output power at constant current, the single-facet slope efficiency is improved by factor of 2 and the threshold current is reduced by approximately 20% as compared to the device without micro-mirror. Both, variation of threshold current density and slope efficiency shall now be taken to estimate the internal losses and the transparency losses. According to [6] threshold current follows the equation

$$i_{th} = \frac{qv_g}{\tau_c G_N} \left[ \frac{N_0 G_N}{v_g} \left( \alpha_{\text{mir}} + \langle \alpha_{\text{int}} \rangle + \alpha_{\text{transp}} \right) \right]$$

with $N_0$ being equilibrium number of electrons, $\tau_c$ the carrier lifetime, $v_g$ the group velocity, $\langle \alpha_{\text{int}} \rangle$ and $\alpha_{\text{mir}}$ the internal and distributed mirror losses and $\alpha_{\text{transp}}$ the transparency losses. For a standing wave laser with two facet reflectivities $R_1, R_2$ and resonator length $L$, the mirror losses are given by

$$\alpha_{\text{mir}} = \frac{1}{2L} \ln \frac{1}{R_1 R_2}$$

Since $R_1$ represents the HR-coated facet ($R_1 = 0.95 \ldots 0.98$) and $\ln(1/x) \gg 1 - x$ for $x \gg 1$, (1) can be rewritten and simplified by introducing the constants $A$, $B$

$$i_{th} = A \left[ B + \langle \alpha_{\text{int}} \rangle + \frac{1}{2L} \ln \frac{1}{R_{2,\text{eff}}} \right] \approx A \left[ B + \langle \alpha_{\text{int}} \rangle + \frac{1}{2L} \ln \frac{1}{R_{2,\text{eff}}} \right]$$

Comparison with literature gives typical values of $\langle \alpha_{\text{int}} \rangle$ between 35 cm$^{-1}$ and 45 cm$^{-1}$ [7, 8], therefore the term containing $R_1$ can be neglected. For simulated values of $R_{2,\text{eff}}$, (3) can be used to fit the internal losses $\langle \alpha_{\text{int}} \rangle$. The obtained values of $\langle \alpha_{\text{int}} \rangle$ are between 58 cm$^{-1}$ and 67 cm$^{-1}$ depending on the particular device. Similarly, starting from the output power
Fig. 3. Estimation of internal losses in dependence of (a) threshold current density variation and (b) changes in the slope efficiency.

\[ P_{\text{opt}} \text{ for a standing wave laser, the one facet slope efficiency for the HR-coated facet could be derived according to } [9] \]

\[ \eta_{kd} \propto \frac{\partial P_{\text{opt}}}{\partial i} \propto \frac{1}{2L} \ln \left( \frac{1}{R_{z,\text{eff}}} \right) + \frac{T_1}{(i > i_{\text{th}})} + (\alpha_{\text{int}}) + T_1 \]

\[ (i > i_{\text{th}}) \]

\[ P_{\text{opt}}, \text{ the optical output power, } T_1 \text{ the transmittance of the HR-coated facet, } (\alpha_{\text{int}}) \text{ the internal losses, and } i, i_{\text{th}} \text{ the forward and threshold currents, respectively. Since slope efficiency is taken above laser threshold and represents a differential figure it only considers internal losses like waveguide and scattering losses. The obtained values for these are in the range of } 27 \text{ cm}^{-1} \text{ and } 46 \text{ cm}^{-1}. \]

4. Conclusion

We examined the influence of an external micro-mirror to the L-I-characteristics of GaN-based laser diodes. Both, threshold current density and differential slope efficiency can be improved significantly by increasing the effective mirror reflectance. Modeling of the effective mirror reflectance allows the estimation of internal losses from change of threshold current density and differential quantum efficiency in dependence on adjusted mirror reflectivity. Depending on the particular device values of \( (\alpha_{\text{int}}) \) between 27 cm\(^{-1}\) and 46 cm\(^{-1}\)
for derivation from differential quantum efficiency are obtained, which is in good agreement with data extracted from laser threshold of different cavity lengths (30–50 cm⁻¹). For variation of current threshold internal losses in the range of 58 cm⁻¹ to 67 cm⁻¹ have been calculated. The values of internal losses estimated from threshold behavior contain additionally transparency losses and are therefore slightly increased.

References


